Formulas for Calculating a Grounding Resistance of Simple Forms with Ground Enhancement Material

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Abstract

Solution of ground enhancement material application for decreasing resistance of grounding system is a current problem that draws much attention from scientists [(Lightning Protection International PTY), (Van Dinh Anh and his Group, 2004)], especially, a grounding system is installed in small area or high resistivity of Soil. In order to determine the grounding resistances of simple forms (horizontal rod or vertical rod. we can use the given software (ERICO Company LTD) or the calculating formulas (Chuong Ho Van Nhat, 2010). This paper presents some other formulas for calculating a grounding resistance of simple forms with ground enhancement material. Calculated results from the formulas of this paper were verified by the results of (Chuong Ho Van Nhat, 2010) and the results from the grounding calculating software of ERICO Company in Australia.

Keywords

Resistivity of Soil; Grounding System; Horizontal and Vertical Rod; Ground Enhancement Material (GEM)

Calculating method

Grounding Resistance of Single Vertical Rod

1) GEM Layer of Cylinder Form

Single vertical rod with diameter d , length l and resistivity ρ3 is buried in the ground with depth t . It is environed by the GEM layer with resistivity ρ2 and the soil environment with resistivity ρ1 (see FIG .1).

Choosing coordinates system as in FIG.2 and considering the potential at point (x,z), according to (Nathan Ida, 2000), we have

$$\varphi(z,x)=\int\frac{I\rho dz}{4\pi l\sqrt{z^2+x^2}} \qquad (1)$$

Where I is the current flows through the rod, ρ is the resistivity of environment at point (x, z) and l is the length of rod.

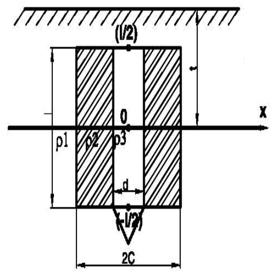

FIG 1 SINGLE VERTICAL ROD IN UNIFORMED ENVIRONMENT

For simplifying in calculation, the method of mirror images is used and the soil is considered as a uniformed environment with resistivity ρ1 and we do not mention influence of temperature upon the environment containing grounding system. So, the potential along the rod is calculated as follows:

$$\varphi(x)=\int_{-l/2}^{2t+l/2}d\varphi(z,x)=\int_{-l/2}^{l/2}d\varphi(z,x)+\int_{2t-1/2}^{2t+1/2}d\varphi(z,x)$$
$$=\frac{I\rho}{4\pi l}\left[2Arsh\left(\frac{l}{2x}\right)+Arsh\left(\frac{2t+l/2}{x}\right)-Arsh\left(\frac{2t-l/2}{x}\right)\right] \qquad (2)$$

Replacing $Arsh\,(x)=\ln\left[(x)+\sqrt{x^2+1}\right]$ and similarly for other variables of (2), we receive:

$$\varphi(x)=\frac{I\rho}{4\pi l}\left[2\ln\left(\frac{\sqrt{l^2+4x^2}+l}{2x}\right)+\ln\left(\frac{\sqrt{(4t+l)^2+4x^2}+4t+l}{\sqrt{(4t-l)^2+4x^2}+4t-l}\right)\right] \qquad (3)$$

Grounding Resistance of Vertical Rod with the GEM

This resistance consists of three components (see FIG. 2):

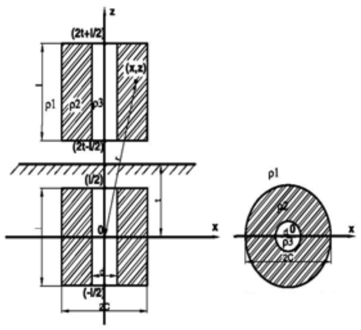

FIG.2 GROUNDING ROD WITH GEM

1) The Component in the Metal Environment

The potential function

$$\Delta\varphi_1 = \varphi(0) - \varphi(d/2)$$

with ρ = ρ3. From (3), we have:

$$\varphi(0) = \frac{I\rho_3}{4\pi l}\left[\ln\left(\frac{4t+l}{4t-l}\right)\right] \quad (4)$$

and

$$\varphi(d/2) = \frac{I\rho_3}{2\pi l}\left[\ln\left(\frac{2l}{d}\right) + \frac{1}{2}\ln\left(\frac{4t+l}{4t-l}\right)\right] \quad (5)$$

From (4) and (5), we receive

$$\Delta\varphi_1 = \frac{I\rho_3}{2\pi l}\left[\ln\left(\frac{2l}{d}\right)\right] \quad (6)$$

So, the resistance value of this component

$$R_1 = \frac{\Delta\varphi_1}{I} = \frac{\rho_3}{2\pi l}\left[\ln\left(\frac{2l}{d}\right)\right] \quad (7)$$

2) The Component in the GEM Environment

The potential function

$$\Delta\varphi_2 = \varphi(d/2) - \varphi(C)$$

with ρ = ρ2.

when x= d /2, x=C and note that $\left(\frac{d}{2}\right)^2 << (4t+l)^2$, we have:

$$\Delta\varphi_2 = \frac{I\rho_2}{2\pi l}\left[\ln\left(\frac{2l}{d}\right) + \frac{1}{2}\ln\left(\frac{4t+l}{4t-l}\right) - \ln\left(\frac{\sqrt{(l^2+4C^2)}+l}{2C}\right) - \frac{1}{2}\ln\left(\frac{\sqrt{(4t+l)^2+4C^2}+4t+l}{\sqrt{(4t-l)^2+4C^2}+4t-l}\right)\right] \quad (8)$$

and

$$R_2 = \frac{\Delta\varphi_2}{I}$$

$$R_2 = \frac{\rho_2}{2\pi l}\left[\ln\left(\frac{2l}{d}\right) + \frac{1}{2}\ln\left(\frac{4t+l}{4t-l}\right) - \ln\left(\frac{\sqrt{(l^2+4C^2)}+l}{2C}\right) - \frac{1}{2}\ln\left(\frac{\sqrt{(4t+l)^2+4C^2}+4t+l}{\sqrt{(4t-l)^2+4C^2}+4t-l}\right)\right] \quad (9)$$

3) The Component in the Soil Environment

The potential function $\Delta\varphi_3 = \varphi(C) - \varphi(\infty)$ with ρ = ρ1. Because of φ(∞) = 0, $\Delta\varphi_3 = \varphi(C)$. So:

$$\Delta\varphi_3 = \varphi(C) = \frac{I\rho_1}{4\pi l}\left[2\ln\left(\frac{\sqrt{l^2+4C^2}+l}{2C}\right) + \ln\left(\frac{\sqrt{(4t+l)^2+4C^2}+4t+l}{\sqrt{(4t-l)^2+4C^2}+4t-l}\right)\right] \quad (10)$$

$$R_3 = \frac{\Delta\varphi_3}{I} = \frac{\rho_1}{2\pi l}\left[\ln\left(\frac{\sqrt{l^2+4C^2}+l}{2C}\right) + \frac{1}{2}\ln\left(\frac{\sqrt{(4t+l)^2+4C^2}+4t+l}{\sqrt{(4t-l)^2+4C^2}+4t-l}\right)\right] \quad (11)$$

At last, the total resistance value:

$$R_C = R_1 + R_2 + R_3$$

In reality, a thickness of the chemical layer C is very smaller than the rod length l (C<< l). Therefore, from (7), (9) and (11), we have:

$$R_C = \frac{1}{2\pi l}\left[(\rho_1)\ln\left(\frac{l\sqrt{4t+l}}{C\sqrt{4t-l}}\right) + \rho_2\ln\left(\frac{2C}{d}\right) + \rho_3\ln\left(\frac{2l}{d}\right)\right] \quad (12)$$

Grounding Resistance of Equivalent Vertical Rod

For calculating grounding resistance of simple forms with or without the GEM, we wish to use only a form of a common formula. So, the formula for calculating such equivalent grounding resistance value will be found in this paper.

We can consider that the single vertical rod is only buried in one single soil layer consisting of GEM and natural soil with their equivalent resistivity ρ_{eq}. This resistance value consists of only two components (see FIG.3).

Calculating similarly as the above points, we have:

1) The Component in the Metal Environment

$$R_1' = \frac{\rho_3}{2\pi l}\left[\ln\left(\frac{2l}{d}\right)\right] \quad (13)$$

2) The Component in the Equivalent Soil Environment

$$R_{eq}' = \frac{\rho_{eq}}{4\pi l}\left[2\ln\left(\frac{2l}{d}\right) + \ln\left(\frac{(4t+l)}{(4t-l)}\right)\right] \quad (14)$$

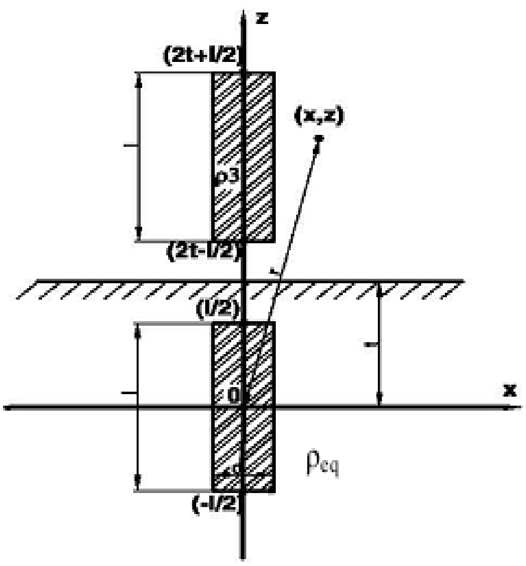

FIG .3 VERTICAL GROUNDING ROD AND ITS IMAGE

Total resistance: $R_C = R'_1 + R'_3$

$$R_C = \frac{1}{2\pi l}\left[(\frac{\rho_{eq}}{2})\ln\left(\frac{(4t+l)}{(4t-l)}.\frac{4l^2}{d^2}\right) + \rho_3.\ln(\frac{2l}{d})\right] \quad (15)$$

Hence, In order to determine the equivalent resistivity we will equalize (12) and (15), from this

$$\frac{\rho_1}{2\pi l}\left[\ln\left(\frac{l\sqrt{4t+l}}{C\sqrt{4t-l}}\right)\right] + \frac{\rho_2}{2\pi l}\left[\ln\left(\frac{2C}{d}\right)\right] - \\ - \frac{\rho_{eq}}{4\pi l}\left[2\ln\left(\frac{2l}{d}\right) + \ln\left(\frac{(4t+l)}{(4t-l)}\right)\right] = 0$$

or

$$\rho_1\left[\ln\left(\frac{l\sqrt{4t+l}}{C\sqrt{4t-l}}\right)\right] + \rho_2\left[\ln\left(\frac{2C}{d}\right)\right] - \\ - \rho_{eq}\left[\ln\left(\frac{2l}{d}\right) + \ln\left(\frac{\sqrt{4t+l}}{\sqrt{4t-l}}\right)\right] = 0$$

The equivalent soil resistivity will be

$$\rho_{eq} = \frac{\ln\left[\left(\frac{l\sqrt{4t+l}}{C\sqrt{4t-l}}\right)^{\rho_1} \times \left(\frac{2C}{d}\right)^{\rho_2}\right]}{\ln\left(\frac{2l\sqrt{4t+l}}{d\sqrt{4t-l}}\right)} \quad (16)$$

Hence, we can count as single grounding vertical rod (with parameters d, l, ρ_3) that is only buried in one single soil layer with equivalent resistivity ρ_{eq}. This equivalent resistivity is calculated by equation (16) (see FIG.4).

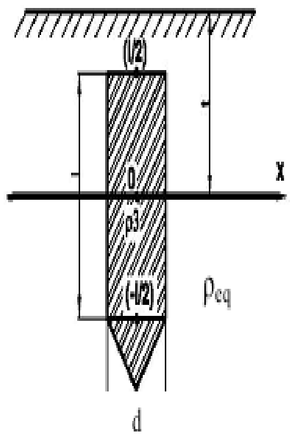

FIG .4 VERTICAL ROD IN EQUIVALENT SOIL ENVIRONMENT

In reality, $\rho_3 \approx 0$, we have from (15):

$$R_C = \frac{\rho_{eq}}{2\pi l}\left[\ln\frac{2l}{d} + \frac{1}{2}\ln\left(\frac{(4t+l)}{(4t-l)}\right)\right] \quad (17)$$

with ρ_{eq} is calculated by (16) . If there is not the GEM layer, then $\rho_{eq} = \rho_1$ and (17) will become: (see (Alya B. Joffe, 2010), (ANSI/IEEE Std 80-2000), (Chuong Ho Van Nhat, 2009), (Viet Hoang, 2010))

$$R_C = \frac{\rho_1}{2\pi l}\left[\ln\frac{2l}{d} + \frac{1}{2}\ln\left(\frac{(4t+l)}{(4t-l)}\right)\right] \quad (18)$$

3) *GEM Layer of Rectangular Prism Form*

We consider the single vertical rod with diameter d, length l and resistivity ρ3. It is surrounded by the GEM layer with resistivity ρ2 and the soil environment with resistivity ρ1. It is fixed in the ground with the depth t and the GEM layer has the dimensions $a \times b \times l$ (see FIG.5)

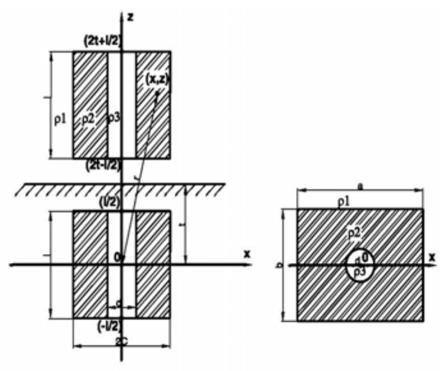

FIG.5 SINGLE GROUNDING VERTICAL ROD WITH THE GEM LAYER

In this case, we can convert the rectangular prism form into a cylinder form with its diameter C [7]

$$C = \sqrt{\frac{ab}{\pi}} \tag{19}$$

and we will receive the formulas as in the case of the GEM layer of cylinder form.

Grounding Resistance of Single Horizontal Rod

1) GEM Layer of Cylinder Form

Single horizontal rod with diameter d, length l and resistivity ρ_3 is fixed in the ground with the depth t. It is environed by the GEM environment with resistivity ρ_2 and the soil environment with resistivity ρ_1 (see FIG. 6)

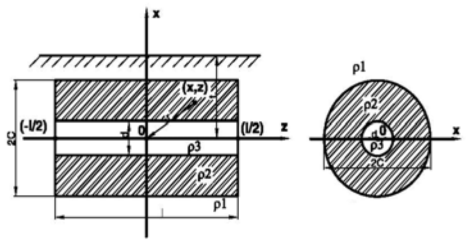

FIG.6 SINGLE GROUNDING HORIZONTAL ROD WITH THE GEM LAYER

Applying (1) and after some transformations, we found the magnetic field that is created by the horizontal rod at the point (x, z)

$$\varphi_1(x) = \frac{I\rho}{2\pi l}\ln\left[\left(\frac{l}{2x}\right) + \sqrt{\left(\frac{l}{2x}\right)^2 + 1}\right] \tag{20}$$

and the magnetic field is created by the image of the horizontal rod at the point (x, z):

$$\varphi_2(x) = \frac{I\rho}{2\pi l}\ln\left[\left(\frac{l}{2(2t-x)x}\right) + \sqrt{\left(\frac{l}{2(2t-x)}\right)^2 + 1}\right] \tag{21}$$

Grounding Resistance of Horizontal Rod with the GEM

We use the calculating method as at the above point and receive the results as follows :

1) The Component in the Metal Environment

$$R_1 = \frac{\Delta\varphi_1}{I} = \frac{\rho_3}{2\pi l}\ln\left(\frac{d}{2l}\right) \tag{22}$$

2) The Component in the GEM Environment

$$R_2 = \frac{\Delta\varphi_2}{I} = \frac{\rho_2}{2\pi l}\ln\left(\frac{C(2t-C)}{dt}\right) \tag{23}$$

3) The Component in the Soil Environment

$$R_3 = \frac{\Delta\varphi_3}{I} = \frac{I\rho_1}{2\pi l}\ln\left(\frac{l^2}{C(2t-C)}\right) \tag{24}$$

So, total resistance: $R_T = R_1 + R_2 + R_3$

$$R_T = \frac{1}{2\pi l}\left[(\rho_1)\ln\left(\frac{l^2}{C(2t-C)}\right) + \rho_2\ln\left(\frac{C(2t-C)}{dt}\right) + \rho_3\ln\frac{d}{2l}\right] \tag{25}$$

Grounding Resistance of Equivalent Horizontal Rod

We use the calculating method as at the above point and receive the results as follows:

1) The Component in the Metal Environment

$$R_1' = \frac{\rho_3}{2\pi l}\left[\ln\left(\frac{d}{2l}\right)\right] \tag{26}$$

2) The Component in the Equivalent Soil Environment

$$R'_3 = \frac{\rho_{eq}}{2\pi l}\ln\left(\frac{l^2}{dt}\right) \tag{27}$$

Total resistance: $R_T = R'_1 + R'_3$

$$R_T = \frac{1}{2\pi l}\left[\rho_{eq}\ln\left(\frac{l^2}{dt}\right) + \rho_3\ln\left(\frac{d}{2l}\right)\right] \tag{28}$$

Hence, In order to determine the equivalent resistivity we will equalize (25) and (28), from this

$$\rho_1\ln\left(\frac{l^2}{C(2t-C)}\right) + \rho_2\ln\left(\frac{C(2t-C}{dt}\right) - \rho_{eq}\ln\left(\frac{l^2}{dt}\right) = 0$$

The equivalent soil resistivity will be

$$\rho_{eq} = \frac{\ln\left[\left(\frac{l^2}{C(2t-C)}\right)^{\rho_1} \times \left(\frac{C(2t-C)}{dt}\right)^{\rho_2}\right]}{\ln\left(\frac{l^2}{dt}\right)} \tag{29}$$

So, we can count as single grounding horizontal rod (with parameters d, l, ρ_3) that is only buried in one single soil layer with equivalent resistivity ρ_{eq}. This equivalent resistivity is calculated by equation (29) (see FIG.7).

In reality, $\rho_3 \approx 0$, from (28) we have:

$$R_T = \frac{\rho_{eq}}{2\pi l}\left[\ln\left(\frac{l^2}{dt}\right)\right] \tag{30}$$

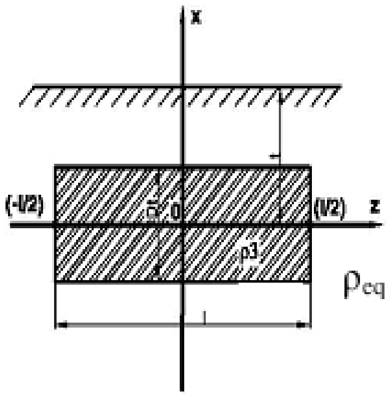

FIG.7 GROUNDING HORIZONTAL ROD IN EQUIVALENT SOIL ENVIRONMENT

When there is not GEM, then $\rho_{eq} = \rho_1$ and the formula (30) will become: (see [1], [2], [3] and [10])

$$R_T = \frac{\rho_1}{2\pi l}\left[\ln\left(\frac{l^2}{dt}\right)\right] \tag{31}$$

3) GEM Layer of Rectangular Prism Form

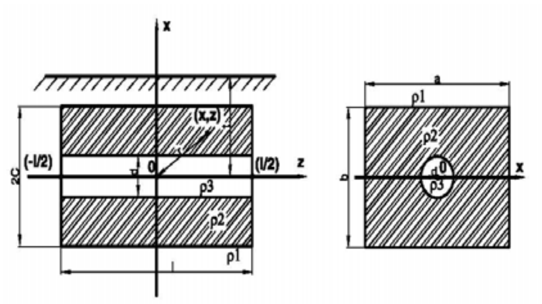

FIG.8 SINGLE HORIZONTAL ROD WITH THE GEM

Similar as above, we can convert a rod of the rectangular prism form (see FIG.8) into a cylinder with diameter C is calculated by formula (19) and receive the formulas as in the case of the cylinder form GEM layer.

In summary, in order to calculate a grounding resistance of simple vertical rod, we use the formula

$$R_C = \frac{\rho_{eq}}{2\pi l}\left[\ln\frac{2l}{d} + \frac{1}{2}\ln\left(\frac{(4t+l)}{(4t-l)}\right)\right]$$

without GEM then $\rho_{eq} = \rho_1$

with GEM then

$$\rho_{eq} = \frac{\ln\left[\left(\frac{l\sqrt{4t+l}}{C\sqrt{4t-l}}\right)^{\rho_1} \times \left(\frac{2C}{d}\right)^{\rho_2}\right]}{\ln\left(\frac{2l\sqrt{4t+l}}{d\sqrt{4t-l}}\right)}$$

and in order to calculate a grounding resistance of simple horizontal rod, we use the formula

$$R_T = \frac{\rho_{eq}}{2\pi l}\left[\ln\left(\frac{l^2}{dt}\right)\right]$$

without GEM then $\rho_{eq} = \rho_1$

with GEM then

$$\rho_{eq} = \frac{\ln\left[\left(\frac{l^2}{C(2t-C)}\right)^{\rho_1} \times \left(\frac{C(2t-C)}{dt}\right)^{\rho_2}\right]}{\ln\left(\frac{l^2}{dt}\right)}$$

Calculating application

Calculating Data

We use the following data: resistivity of soil 200 Ωm; resistivity of GEM 20 ΩCm; resistivity of metal rod 0.000172 ΩCm; diameter of GEM layer of cylinder form 20Cm ; side of GEM layer of square form 20Cm ; the depth of horizontal or vertical rod 50Cm.

Comparing Results Between This Paper and Formulas of (Chuong Ho Van Nhat, 2010)

1) *Surveying Vertical Rod*

TABLE 1 COMPARING RESULTS BETWEEN THIS PAPER AND FORMULAS OF (Chuong Ho Van Nhat, 2010)

Length (m)	3	4	5	6	7	8	9	10
Paper	47.6	35.9	29.3	25.0	21.8	19.4	17.6	16.1
(Chuong Ho Van Nhat, 2010)	47.6	35.9	29.3	25.0	21.8	19.4	17.6	16.1

TABLE 2 COMPARING RESULTS BETWEEN THIS PAPER AND FORMULAS OF (Chuong Ho Van Nhat, 2010)

Length(m)	3	4	5	6	7	8	9	10
Paper	46.4	35.8	28.6	24.3	21.3	19.0	17.2	15.7
(Chuong Ho Van Nhat, 2010)	46.4	35.8	28.6	24.3	21.3	19.0	17.2	15.7

2) *Surveying Horizontal Rod*

TABLE 3 COMPARING RESULTS BETWEEN THIS PAPER AND FORMULAS OF (Chuong Ho Van Nhat, 2010)

Length(m)	5	10	15	20	25	30	35	40
Paper	35.8	22.3	16.6	13.3	11.2	9.7	8.6	7.7
(Chuong Ho Van Nhat, 2010)	35.8	22.3	16.6	13.3	11.2	9.7	8.6	7.7

TABLE 4. COMPARING RESULTS BETWEEN THIS PAPER AND FORMULAS OF (Chuong Ho Van Nhat, 2010)

Length(m)	5	10	15	20	25	30	35	40
Paper	35.1	21.9	16.3	13.2	11.1	9.6	8.5	7.7
(Chuong Ho Van Nhat, 2010)	35.1	21.9	16.3	13.2	11.1	9.6	8.5	7.7

3) Remark

From the data in TABLES 1, 2, 3 and 4 we realize that the formulas of this paper and (Chuong Ho Van Nhat, 2010) give the same results.

Comparing Results between This Paper and GEM Software of ERCO Company

1) Surveying Vertical Rod

TABLE 5 COMPARING RESULTS BETWEEN THIS PAPER AND SOFTWARE OF ERICO COMPANY

Length(m)	3	4	5	6	7	8	9	10
Paper	47.6	35.9	29.3	25.0	21.8	19.4	17.6	16.1
Software	40.2	32.5	27.4	23.8	21.1	19.0	17.3	15.9

TABLE 6 COMPARING RESULTS BETWEEN THIS PAPER AND SOFTWARE OF ERICO COMPANY

Length(m)	3	4	5	6	7	8	9	10
Paper	46.4	35.8	28.6	23.1	21.3	19.0	17.2	15.7
Software	39.0	31.5	26.6	23.1	20.6	18.5	16.9	15.5

2) Surveying Horizontal Rod

TABLE 7 COMPARING RESULTS BETWEEN THIS PAPER AND SOFTWARE OF ERICO COMPANY

Length(m)	5	10	15	20	25	30	35	40
Paper	35.8	22.3	16.6	13.3	11.2	9.7	8.6	7.7
Software	32.1	20.4	15.4	12.4	10.5	9.1	8.1	7.3

TABLE 8. COMPARING RESULTS BETWEEN THIS PAPER AND SOFTWARE OF ERICO COMPANY

Length(m)	5	10	15	20	25	30	35	40
Paper	35.1	21.9	16.3	13.2	11.1	9.6	8.5	7.7
Software	31.3	20.1	15.1	12.2	10.4	9.0	8.0	7.2

3) Remark

From the data in TABLES 5, 6, 7 and 8 we realize that the formulas of this paper and the software of ERICO Company give the calculating results with the errors that are not great (about 15%) with short length of rod and are approximate with long.

Conclusions

1). We received other formulas for calculating the resistance of simple grounding forms with influence of the GEM in comparison with (Chuong Ho Van Nhat, 2010).

2). We received formulas for calculating the equivalent resistivity of the GEM and natural soil layer.

3). We can use a common formula for calculating the resistance of simple grounding forms with or without the GEM.

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Authors Introduction

Chuong Ho Van Nhat was born in 1954, Hue province, Vietnam. He received bachelor of science degree in electrical engineering from Ho Chi Minh City University of Technology in 1977 and Philosophy Doctor degree in High Voltage Engineering from Kiev Polytechnique University, Ukraine in 1997. Now, he has been as senior lecturer of Power Systems Department of HCMCity University of Technology. His main research interests concentrate on the fields of Grounding System, Overvoltages in Power Systems and Measurements on High Voltage.

Tung Nguyen Thanh was born in 1980, TraVinh province, Vietmam. He received bachelor of science degree in electrical and electronics engineering in 2007 and master of science degree in 2012 from University of Technical Education HCMC, HCM City, Vietnam in 2007. He has been as lecturer of Dong Thap Vocational College. His main research interests concentrate on the fields of Grounding System and Renewal Energy.

Lan Ngo Kim was born in 1976, Vinh Phuc province, Vietnam. He received bachelor of science degree in electrical and electronics engineering from Ho Chi Minh City University of Technology - HUTECH in 2001 and and master of science degree in electrical engineering from University of Technical Education HCMC, HCM City, Vietnam in 2009. He has been as lecturer of Dong Nai Vocational College. His main research interests concentrate on the fields of Grounding and Automation in Power Systems.